

Attitude Determination by Using Horizon and Sun Sensors

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Abstract

The Pointing and Alignment Workstation (PAWS) developed by Teledyne Brown Engineering (TBE) has successfully supported the first and second Atmospheric Laboratory for Applications and Science (ATLAS 1, 2) Spacelab missions for NASA. The primary PAWS objective was to provide realtime pointing information to instruments whose line of sight is dependent on Shuttle attitude and to study/quantify the causes and effects of Shuttle and payload pointing errors. In addition to Shuttle IMU attitude information, PAWS used atmospheric science sensors data to determine the spacecraft attitude. PAWS successfully achieved these goals by acquiring and processing data during the ATLAS 1, 2 mission. This paper presents the attitude determination algorithm, realtime processing, and results of post mission analysis. The findings of this study include the quality of the horizon sensor and IMU measurements as well as accuracy of attitude processor algorithm.

Keywords

Attitude determination
Realtime

Horizon sensor
Oblateness

Sun sensor
Pointing

1. Introduction

Spacecraft are often used as a platforms for pointing instruments at subjects of scientific interest. On the ATLAS series of NASA/Spacelab missions several of the solar and astronomy instruments are attached to pallets mounted in the Space Shuttle bay and have a fixed optical axis relative to the Shuttle. Although some atmospheric experiments have a non-fixed optical axis and can move the line-of-sight to their science interests, they are also dependent on the Shuttle attitude control system and the attitude information from the spacecraft Inertial Measurement Unit (IMU) to achieve the desired scientific goals. Instrument pointing errors are caused by thermal, mechanical, calibration, Shuttle attitude control system imperfections and the IMU drift. The consequence of this is that although the Shuttle's attitude information indicates that the instrument is viewing the intended target, this is never exactly true. These uncontrollable pointing errors sources perturb the instrument's pointing and orient the optical axis somewhat off the desired. Also, the unknown bias of IMU attitude information can introduce significant error in science data analyses, especially for a remote sensing experiment.

During the atmospheric science segments of the ATLAS missions the Shuttle was flown in a bay to earth, tail or nose into the velocity vector attitude. This local attitude was maintained for

up to 10 hours at a time since it is the optimum for instruments studying the earth's atmosphere continuously. All of the ATLAS instruments are critically dependent upon Shuttle IMU attitude information. For instance, the Millimeter-Wave Atmospheric Sounder (MAS) is a passive total power microwave radiometer-spectrometer for Earth limb observations from space. It measures the strength of millimeter waves radiation emitted by various constituents in the atmosphere in the height range between 20 km and 100 km. This remote sensing experiment needs Shuttle state vector (position and velocity) and its attitude quaternion to determine the spatial sensing location. The Shuttle's on-board state vectors along its flight trajectory are constantly updated based on TDRSS and the ground station tracking. Shuttle trajectory deviation is believed well within the error budgets. However, Shuttle attitude information relies totally on its own IMU. The advertised Shuttle IMU accuracy is ± 0.5 degrees (3 sigma) with resolution of ± 0.1 degree. A ± 0.1 degree error in roll can introduce about 6 kilometer altitude error at 300 kilometer altitude orbit during the earth limb observation. This error magnitude is unacceptable for the MAS experiment.

The primary PAWS objective is to refine the accuracy of attitude knowledge by using existing on-board scientific instrument data as pointing information. Since the Shuttle was not pointing a specific axis for atmospheric targets (other than the center of the earth), the optical axis of some instruments are designed to acquire and track the targets of scientific interest. A survey of the atmospheric instruments flying on ATLAS 1 by the PAWS team determined that the Grille experiment was the only atmospheric sensor with adequate pointing knowledge to be useful. However, in order to construct a complete coordinate frame defining the instrument's platform attitude it requires pointing information from another target besides Grille. This is due to the fact that the instruments are pointing devices which basically can only define an axis in space. Fortunately, two Horizon Sensors (HS's) were located on the aft pallet of the ATLAS 1 mission. These devices were designed to provide precise attitude information based on the actual limb of the earth. Since Grille and HS have two different targets, the sun and earth limb respectively, a Grille/HS attitude processor was developed to determine attitude information from instruments during

the local attitude hold. The Grille/HS attitude processor can compute the spacecraft platform attitude semi-independently of IMU data by combining these two pieces of pointing information. This paper first briefly describes both Grille and Horizon Sensor hardware. Then the mathematical model for the Grille/HS attitude processor is presented. Also an attitude determination algorithm by using single sensor data with partial IMU measurement will be discussed. Finally, the horizon sensor measurement data was examined and the attitude determination processor results were compare with IMU outputs.

2. Grille and Horizon Sensor Instrument Descriptions

Grille Spectrometer

Grille is an experiment designed and built by Belgian Institute for Space Astronomy and National Institute for Aerospace Studies of France [1]. The Grille Spectrometer measures the absorption of infrared radiation during orbital sunrises and sunsets. The spectrometer operates in the wavelength range from 2.5 to 10 micro-meters. The light coming from the Sun through the Earth's atmospheric limb or from the atmospheric limb itself is reflected toward a telescope by an adjustable rectangular plane mirror. The telescope that transmits the light to the spectrometer has a 0.3-m diameter and a 6-m focal length. Two detectors are used simultaneously to cover the entire spectral range. All functions of the instrument are programmable through a microprocessor that is a part of the instrument electronics. A built-in calibration light source allows testing to be performed at any time before and during flight. The instrument provides the measurement of the azimuth and elevation angles of the Sun center based on the instrument frame during observation. Both azimuth and elevation angle measurements are the necessary inputs to the attitude determination algorithm.

Horizon Sensor

ATLAS 1 Horizon Sensor (HS) hardware consists of two Conical Scan Sensors (CSS) and a Conical Scan Electronics Unit (CSE) [2, 3]. The Bolometer of the CSS is an infrared detector which is located at the focal point of the optical wedge. The HSs' objective lens is coated with a filter-type coating which passes light in the 13-16 micron region. This is in the infrared region of the Electromagnetic Spectrum and stimulates the Bolometer. While the field-of-view of the sensor head scans across the Earth and Space, two distinct levels of radiation are received: (1) earth radiation appears as a Black Body at approximately 240 degrees Kelvin; (2) space radiation approximates a black body approaching 0 degrees Kelvin.

The space-to-earth crossing generates a positive-going pulse which enables the charging of two integrator circuits. The charging of one circuit is terminated by a pulse which is generated within the sensor. The other charging circuit is terminated by the earth-to-space negative-going pulse. This process determines pitch and roll. These two angles are the other set of inputs necessary for the Grille/HS attitude determination algorithm.

3. Mathematical Model

Three-axis attitude determination is required to completely

describe a spacecraft attitude. This requires a complete knowledge of two spacecraft-fixed body directions. However, at least three independent measurements are needed. This section depicts the procedures of constructing the attitude matrix or quaternion by using an algebraic method with dual sensor measurements, designated as Grille/HS processor, as well as using a single sensor measurement in conjunction with partial IMU data.

Dual Sensors Algorithm

Figure 3-1 illustrates the characteristics of the single axis attitude determination of using two sets of sensors acquiring two independent targets. In our case, they are the sun and the local earth limb or the earth center. Both the Grille and horizon sensors are mounted on the Shuttle payload bay along the spacecraft Y axis. From the Grille experiment a half cone angle between the sun vector and Grille axis β is measured. From the horizon sensors, both spacecraft roll, ϕ and pitch, θ are measured. The roll is the angle between spacecraft body +Y axis and the local horizontal while the pitch is the angle between spacecraft body +X axis and the local horizontal. Therefore, both β and ϕ measurements have a common axis, i.e. the body +Y and this common axis is one of the two intersections formed by the Grille cone and the horizon sensor roll angle cone.

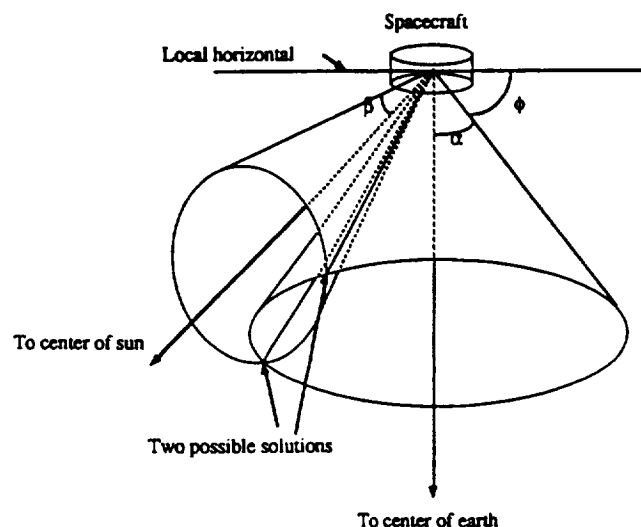


Figure 3.1 Illustration of intersections of sun and Z Nadir cones

Grubin [4] and Wertz [5] presents a simple algorithm of solving intersecting two conical surfaces by using a geometric method. In this study we elected to use an algebraic method which is based on the rotation matrix representation of the attitude.

Since the horizon sensor is mounted along Shuttle body Y axis and most observations are in a Local Vertical and Local Horizontal (LVLH) attitude hold, the LVLH frame is the most convenient to set up as the reference coordinate system. Due to the earth oblateness effect, both horizon sensor pitch and roll angles need to be corrected to the reference LVLH coordinate frame, as illustrated in Figure 3.2. The horizon sensor cone is formed by assigning the cone's z

axis points toward the earth center, i.e. nadir vector, with a half cone angle,

$$\alpha = \pi/2 - \phi \quad (1)$$

where ϕ is the horizon sensor measured roll angle with earth oblateness correction. The spacecraft body Y axis, therefore, lies on the surface of this cone. This cone surface equation can be expressed as

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} - \frac{z^2}{c^2} = 0 \quad (2)$$

where a, b and c are the semi-major axis, semi-minor axis and height of cone, respectively. In our case $a/c = b/c = \tan(\alpha)$ and Equation (2) becomes,

$$\frac{x^2}{\tan(\alpha)^2} + \frac{y^2}{\tan(\alpha)^2} - \frac{z^2}{1} = 0 \quad (3)$$

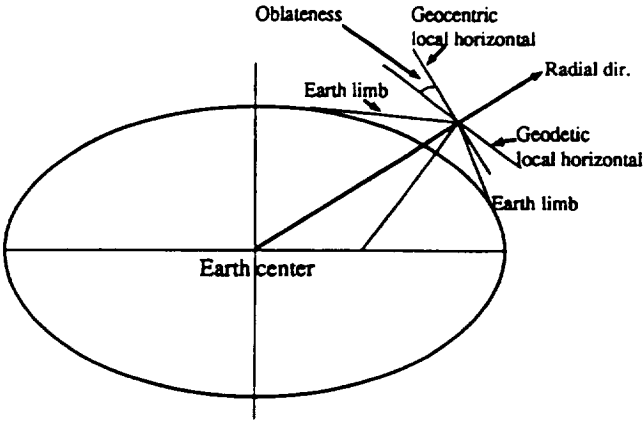


Figure 3-2 Illustration of earth oblateness effect

The second cone surface equation is for the sun sensor, i.e. Grille in our case. Its surface equation can also be expressed as Equation 2 in its line-of-sight (LOS) frame with its z axis pointing toward the sun. The x axis of the LOS frame is defined as the orthogonal to the Z_{LOS} axis lying in the LVLH horizontal plane. The sun sensor cone equation is then transformed from the LOS frame to the LVLH frame where the horizon sensor cone resides. Therefore, the final cone surface equation for the sun sensor can be written in a quadratic form as,

$$a_{11}x^2 + a_{22}y^2 + a_{33}z^2 + 2a_{12}xy + 2a_{13}xz + 2a_{23}yz = 0 \quad (4)$$

with the transformation matrix

$$A = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \quad (5)$$

and matrix A is

$$A = M_{LOS}^{LV} D M_{LOS}^{LV T} \quad (6)$$

where M_{LOS}^{LV} is the transformation matrix from the sun sensor LOS frame to LVLH frame, and

$$M_{LOS}^{LV} = M_I^{LV} * M_{LOS}^I \quad (7)$$

M_I^{LV} is calculated through the spacecraft inertial state vector information, and M_{LOS}^I is constructed by knowing the sun center vector at inertial frame, i.e. LOS as z axis and its perpendicular xy plane.

$$D = \begin{bmatrix} \frac{1}{\tan^2 \beta} & 0 & 0 \\ 0 & \frac{1}{\tan^2 \beta} & 0 \\ 0 & 0 & -1 \end{bmatrix} \quad (8)$$

β is the sun sensor half cone angle. The spacecraft body +Y axis also lies on this sun sensor cone surface. Therefore, the intersections of two cones are the solutions of Equation 2 and 3 by assigning z to a constant length of 1. One of these two solutions is the body +Y axis vector in LVLH frame, designated as \bar{V}_{BLV} . There are several methods of selecting the true solution from a block of data containing ambiguous solutions as discussed in Wertz [5]. There are: (1) to use priori estimation derived from a known initial condition, (2) to correlate a block of solution and find solution with high correlation, (3) to use continuous residual editing process. All these methods are based on an inertial hold axis solution such as spin axis. In our case the spacecraft continues maneuvering while maintaining a LVLH hold, therefore, no such an inertial fixed axis is available. However, since Shuttle downlinks IMU data, its attitude data was available for comparing the two possible solutions. The solution aligned closest to IMU data is assumed to be the correct solution. This dependence makes this algorithm not totally IMU independent. Nevertheless, the objective is to conduct fine attitude determination with high resolution sensor data in order to study the pointing error source contributors.

The second measurement from the horizon sensor is the spacecraft pitch angle which is defined as the angle between body +X axis and the true local horizontal plane. Similar to the horizon sensor roll angle, the earth oblateness corrected pitch angle, θ is the half cone angle with spacecraft body +X axis lying on the pitch cone surface. This conical equation is the same as Equation (2) with $a/c = b/c = \tan(\theta)$,

$$\frac{x'^2}{\tan(\theta)^2} + \frac{y'^2}{\tan(\theta)^2} - \frac{z'^2}{1} = 0 \quad (9)$$

Since the body +X axis, designated as \bar{X}_{BLV} lies on the surface of this conical equation,

$$\bar{X}_{BLV} = (x', y', \pm 1)$$

and is also perpendicular to the body +Y axis,

$$\bar{X}_{B_{LV}} \text{ dot } \bar{Y}_{B_{LV}} = 0 \quad (10)$$

Therefore, the solution of body +X vector, $\bar{X}_{B_{LV}}$ can be found. Finally,

$$\bar{Z}_{B_{LV}} = \bar{X}_{B_{LV}} \times \bar{Y}_{B_{LV}} \quad (11)$$

Therefore, the transformation matrix from the spacecraft body frame to the LVLH frame, M_B^{LV} can be constructed as

$$M_B^{LV} = \begin{bmatrix} \bar{X}_{B_{LV}} & \bar{Y}_{B_{LV}} & \bar{Z}_{B_{LV}} \\ \bar{X}_{B_{LV}} & \bar{Y}_{B_{LV}} & \bar{Z}_{B_{LV}} \end{bmatrix} \quad (12)$$

The spacecraft body to inertial frame transformation matrix can then be calculated.

$$M_B^I = M_{LV}^I * M_B^{LV} \quad (13)$$

Consequently, the spacecraft inertial to body attitude quaternion can be computed.

Single Sensor Algorithm

Another attitude determination algorithm was developed for a single axis pointing information, such as a sun sensor in conjunction of partial IMU attitude information. As mentioned previously, one of the concerns about Shuttle pointing accuracy is thermal effect. As one would expect that the body Y axis suffers the least thermal bending. Therefore, the spacecraft body Y vector computed from IMU attitude data was used in conjunction with the sun sensor pointing data in determine the spacecraft attitude quaternion. Similarly, the combination of the computed IMU body +Y vector and the horizon sensor pointing data can also determine the spacecraft attitude quaternion. Comparison of these three solutions of attitude determination will be discussed in the next section.

4. Data Transmission and Processing

PAWS realtime telemetry subset consists of 160 words of 16 bits per word as described in French and Huang [6]. The measurements of the subset come from two sources. The state vectors and IMU attitude quaternion as well as the associated time tag are from the Shuttle General Purpose Computer (GPC) downlink through both Ku and S bands, known as Orbiter Downlink (OD) data. All Spacelab payload measurements including Grille experiment and the horizon sensors measurements are acquired by on-board experiment computer and downlinked through Experiment Computer Input Output (ECIO) data stream through Ku band. ECIO data stream is downlinked at one hertz with ECIO time tag. The Spacelab Mission Operation Controls (SMOC) located in Huntsville, Alabama then extracts measurements from both sources and constructs a PAWS specific data subset and transmits it to PAWS station through a RS-422 line.

One problem that occurred during realtime operations is the fact both OD and ECIO data have different time tags and they are usually not synchronized. State vector propagation or interpolation is

therefore required for more accurate calculation. The PAWS decommutation software receives the realtime data stream, unpacks the frame, converts data to engineering units and validates the values. The attitude processor then computes the attitude quaternion based on the science data and the bias of this quaternion from the IMU platform. These values are then displayed on the PAWS realtime graphics screen. the PAWS displays are broadcast throughout the SMOC via a video network available for other Principal Investigators (PIs).

5. Results and Discussions

PAWS has supported for two Spacelab mission, ATLAS 1 and ATLAS 2. ATLAS 1 was launched on March 24, 1993, 13:13:40 GMT with 296.1km altitude and 57 degree inclination while ATLAS 2 was launch on on April 8, 1994, 05:29:00 GMT with 293 km altitude, 57 degree inclination. Horizon sensors were flown in both missions and provided a large amount of data for post mission analysis. However, the Grille experiment which provides the sun measurements to PAWS for the attitude determination flew only on the ATLAS 1 mission. This section first presents the characteristics and quality of the horizon sensor measurements as well as the on-board IMU measurements. Then the results of attitude processor solutions are discussed.

Horizon Sensors vs. IMU

As mentioned previously, a typical Shuttle attitude for an atmospheric experiment is an LVLH hold with payload bay facing toward the earth, a so called -Z Nadir/+XVV or -XVV attitude. A typical duration for this attitude hold is about 10 to 15 hours before next IMU alignment. Figures 5-1, 2 shows the horizon sensor measurements, pitch and roll, respectively, for a typical continuous observation period during Acquisition Of Signal (AOS). There are a few data dropout periods in this observation. Both the IMU and HS data match well and the plot clearly illustrates the attitude control deadband of ± 2 degrees for this period. The two horizontal dashed lines in each of the plots indicate the Sun/Moon A and B flags, respectively. When flag A and B value in the plot departs from +2 or -2 this indicates the Sun or Moon appears in the horizon sensor A or sensor B field of view, respectively and the horizon sensor operation switches from the dual sensor mode to the single sensor mode accordingly.

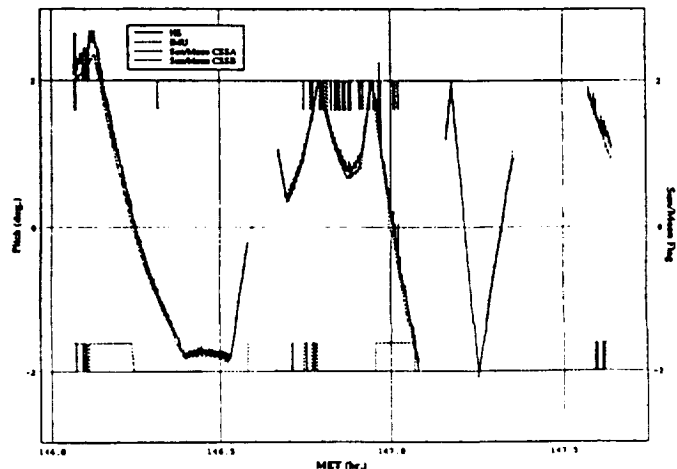


Figure 5-1 Raw horizon sensor pitch data vs. IMU derived pitch

As shown in the figures, when the Sun/Moon occurs, the horizon sensor output deviates from the IMU data significantly (MET 146.1 to 146.2). This difference indicates the accuracy variation between the dual sensor mode and the single sensor mode. Consequently, if the Sun/Moon flag switches on and off quite frequently (MET 146.8 to MET 147.9) it creates high fluctuations in the outputs of both pitch and roll attitude error values. This is extremely critical for an on board instrument, such as MAS which uses the horizon sensor as a pointing reference. An on-board software filtering function is available in Experiment Computer Application Software (ECAS) for correcting this problem.

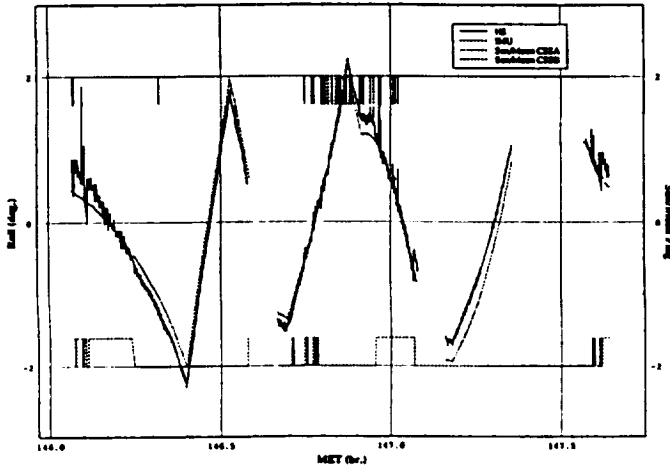


Figure 5-2 Raw horizon sensor roll data vs. IMU derived roll

A study was performed to compare the performance of the horizon sensor to the IMU derived local attitude errors. All of the horizon sensor data examined here is the output when it was in a dual sensor mode with no Sun/Moon interruptions. Figure 5-3 shows the difference between the IMU derived data and the horizon sensor raw data in roll. The sinusoidal error shown in the plot is expected as the IMU derived roll is based on the a spherical earth while the horizon sensor measures true earth limb which is actually a spheroid. The effects of the earth oblateness on pitch and roll measurements depend on the spacecraft altitude, latitude and line-of-sight angle relative to spacecraft body frame. In this study, an

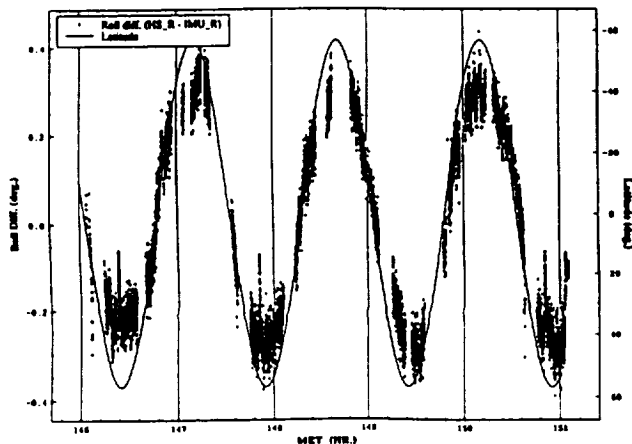


Figure 5-3 Roll difference between raw horizon sensor and IMU

reference spheroid earth model with a flattening factor of $f = 1/298.257$ was used to correct the earth oblateness effects. The magnitude of the earth oblateness effect on the roll angle is about ± 0.16 degree for ATLAS 1 orbit. Figure 5-4 shows the roll angle difference between the horizon sensor and IMU derived roll when the earth oblateness is corrected. However, a sinusoidal error between the horizon sensor and IMU measurements still appears in Figure 5-4. The same phenomenon also occurs in the MAS measurements and ATLAS 2 HS data.

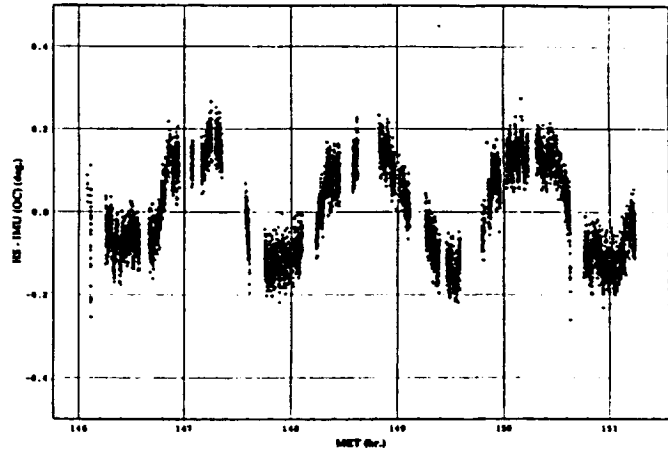


Figure 5-4 Roll difference between horizon sensor roll and oblateness corrected IMU roll

Another suspect of contributing this error is IMU gyro drift. Gyro drift magnitudes are documented for very Shuttle flight whenever IMU alignment is conducted. In order to study the gyro drift effects on the attitude measurement during this LVLH hold attitude, a six degree-of-freedom (6 DOF) trajectory code, SAMSON [7] was used to simulate the ATLAS 2 orbit between two consecutive IMU alignment periods, GMT 7:45, April 10 and GMT 21:12, April 10, 1993. The drift occurs mostly along roll axis and drift rate is about 0.024 degree/hour. The solid line of Figure 5-5 indicates the roll error contributed by the gyro drift during this period. The roll error appears also in a sinusoidal form. This is due to the drift is along an inertial axis, therefore, when a spacecraft is in -Z Nadir/+XVV hold the drift effect propagate to the roll and yaw axis with a period of one orbit. The roll error between

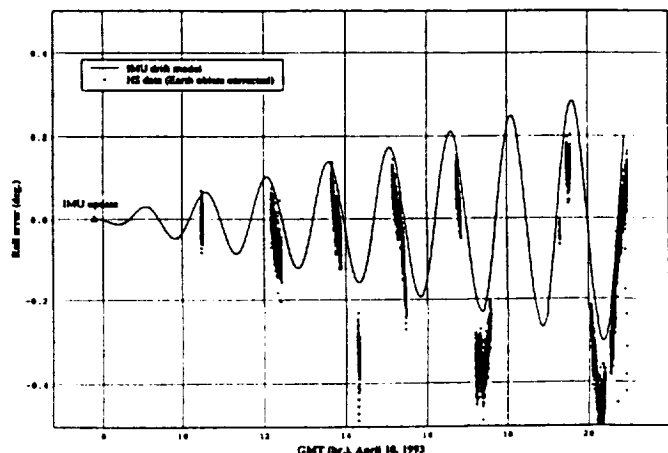


Figure 5-5 Roll difference data vs. IMU drift model

ATLAS 2 horizon sensor measurement and IMU data with oblateness correction were also shown in Figure 5-5. Although the variation of this horizon sensor roll error coincides with simulated data, the magnitude is biased by -0.15 degree. When the simulated data is shifted -0.15 degree to the raw horizon sensor data as shown in Figure 5-6, the data matches very closely. This 0.15 degree error could be due to cloud cover effect, sensor misalignment and/or a thermal bending to the spacecraft since the on-board IMU is mounted about 40 feet away from the sensor location. The standard deviation value for the HS roll variation is about 0.08 degree. With an appropriate filtering function, this variation can be further reduced.

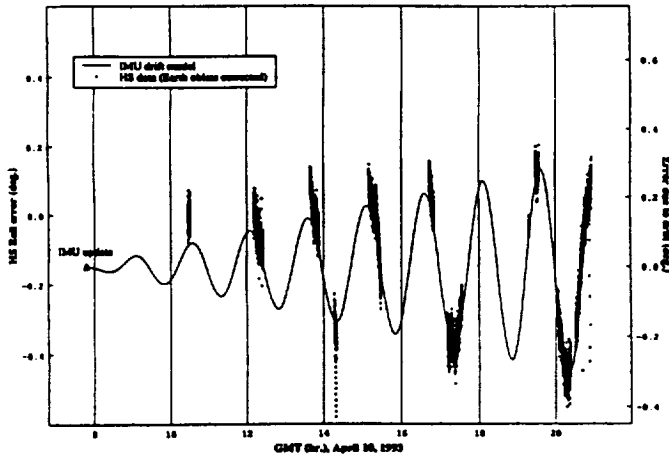


Figure 5-6 Comparison roll difference data with -0.15 degree shifted simulation data

Attitude Processor Results

As mentioned in Section 3, the three-axis attitude determination, Grille/HS attitude processor can only function when both Grille and the horizon sensor have valid measurements at the same time. Its accuracy relies totally on the accuracy of both Grille and the horizon sensor. Although the horizon sensor acquires measurements during most of the LVLH attitude hold period, the Grille instrument was only interested in the brief time period during orbital sunrise and sunset. This amounted to about 5 minutes of data twice per pass. Unfortunately, most of those observations were not Ku band communication covered, consequently, no realtime downlink was available. Only six observation data sets were gathered by PAWS during ATLAS 1 mission, and the amount of data was not enough for detailed long period trend analysis. However, the Grille/HS attitude processor did function and perform well. In addition to the Grille/HS processor, there are a Grille and a HS attitude processors which compute attitude based on their individual measurements. Figure 5-7 shows the result from these three different attitude processors.

In order to compare these three processors, the on-board IMU frame was chosen as the reference frame. Results shown in Figure 5-7 represent the attitude difference between each of the three attitude processors and the referenced IMU frame. As shown in Figure 5-7, the IMU semi-independent attitude processor Grille/HS

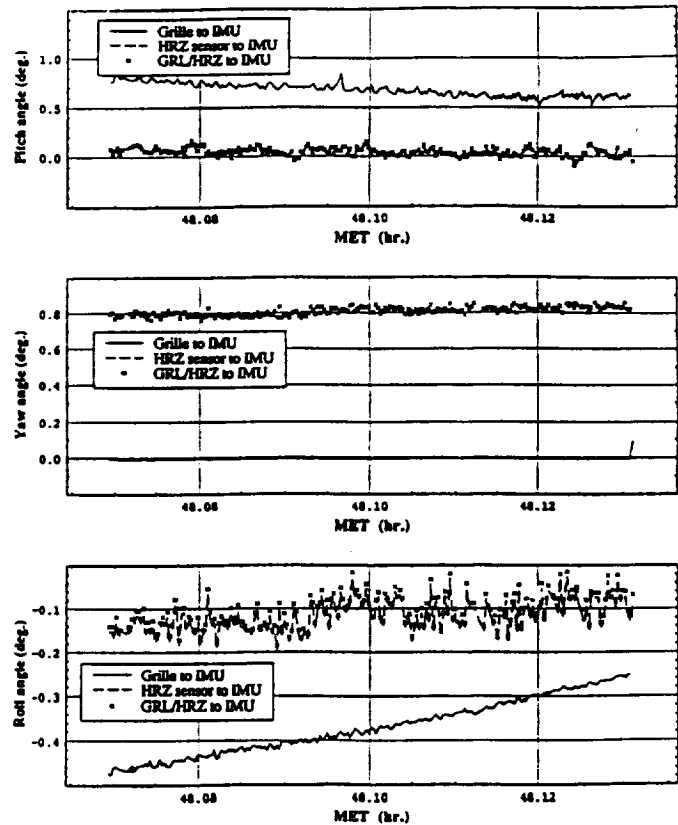


Figure 5-7 Attitude difference from attitude processors to IMU

matches the IMU attitude fairly well with near zero difference in pitch, -0.1 degree difference in roll and 0.8 degree in yaw. All roll, pitch, yaw differences again are based on the on-board IMU reference frame.

As mentioned in Section 3, the two single sensor attitude processors (Grille and HS) require a piece of IMU information (IMU body Y axis). Figure 5-7 shows the HS attitude processor has near zero pitch and -0.1 degree roll difference from IMU attitude. Unlike Grille/HS processor, HS has no independent yaw information because it is assumed that the HS Y axis coincides with IMU body Y axis.

The Grille attitude processor has about 0.7 degree pitch and -0.4 degree roll off from IMU platform. Similar to HS, the Grille yaw difference to IMU is assumed zero.

As discussed previously, the IMU itself has drift and other random walk errors, and there is no way of knowing the true spacecraft attitude which defines the true error for Grille/HS attitude processor. Also both the horizon sensor and Grille has their own measurement error as well as mounting misalignment error, time tagging difference between GPC and Experiment Computer. This aggravates the Grille/HS three-axis attitude determination accuracy problem. Nevertheless, based on the six observation data sets acquired by PAWS, the difference is about 0.2 degree in pitch and roll, 0.9 degree in yaw. These numbers are within the estimated error bound listed in the SEASAT mission experience [2] which uses similar HS and Sun sensors for attitude determination.

6. Conclusions

Although the available processing time for the Grille attitude processor was very brief, the concept of extracting attitude information from an atmospheric science instrument was demonstrated. While the PAWS Grille/HS attitude processor works flawlessly, its accuracy can be aggravated when either HS or Grille pointing deviates. Nevertheless, the unique Grille/HS attitude processor demonstrated the feasibility of realtime attitude determination from two pointing instruments. This algorithm is original resulting from the PAWS work and was proven using realtime flight data.

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